But when the observations came to be finally reduced, it was found that the difference between Colonel Herschel's results at Kew and Greenwich, as shown independently by the three pendulums, had an extreme range of about seven vibrations in the daily vibration number. The cause of these differences was mysterious and inexplicable, and there was no alternative but to swing the pendulums a second time at the two observatories.

The revisionary work was undertaken by the observatory staff at each place, in such intervals of leisure as they could obtain from their regular operations. The final results, by the three pendulums, make the vibration number at Kew in excess of that at Greenwich by 1·56, 1·50, and 0·59, giving an average excess of 1·22.

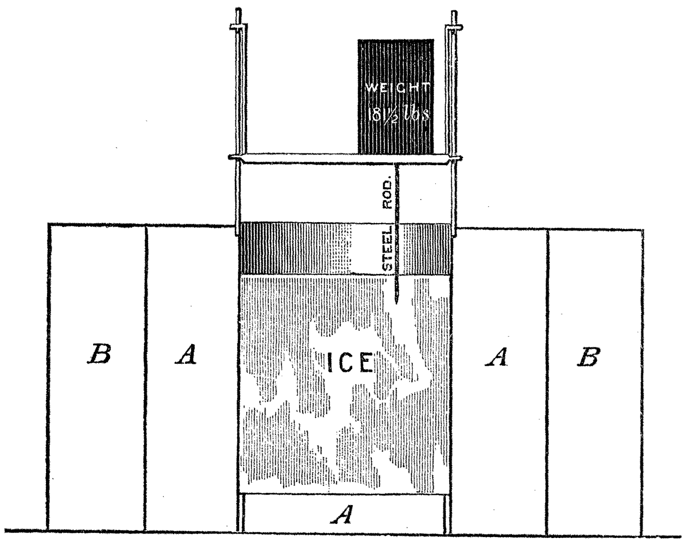
The correction to this quantity for the excess of height of the Greenwich over the Kew Observatory is $-0·58$. Thus, the revisionary operations, reduced to the mean sea-level, make the excess of Kew over Greenwich $= 0·64$ of a vibration, which may be accepted as very fairly probable.

II. "Observations on Pure Ice."—Part II. By Thos. Andrews, F.R.S., M.Inst.C.E. Received May 1, 1890.

The Plasticity of Ice.

In a paper, 'Roy. Soc. Proc.,' vol. 40, 1886, p. 544, I recorded the result of "Observations on Pure Ice and Snow," and having subsequently had occasion to use large quantities of low temperature freezing mixtures in the prosecution of other investigations, it seemed desirable to take advantage of the opportunity, and to further utilise the freezing mixtures in making collaterally the following additional experiments bearing on some of the plastic or viscous properties of ice at various temperatures. Messrs. J. C. McConnel and D. A. Kidd, in their valuable and interesting paper on "The Plasticity of Glacier and other Ice" ('Roy. Soc. Proc.,' vol. 44, 1888, p. 331), remark that "the variation of the plasticity of ice with the temperature is of great interest both for the theory of glaciers and for the explanation of the plasticity itself." I hope, therefore, that the experiments now recorded may assist in affording some information in connexion with this subject. An acquaintance with the causes of the flow of glaciers can scarcely be complete without some accurate experimental knowledge of the plasticity of ice at various temperatures, and it was partly with this object that the following experiments were commenced. The experiments form a continuation of those contained in my former paper. The arrangement of apparatus is described below, and illustrated by the accompanying sketch, fig. 1.

FIG. 1.



The ice for the pure ice experiments was frozen from distilled water contained in a sheet-iron vessel. The inner tank was surrounded both at the sides and bottom by an outer jacket of iron, which was provided with holes at the bottom for the waste liquids to escape. The coolest freezing mixture used, No. 1, consisting of three parts by weight of crystallised calcium chloride and two parts by weight of snow, was placed in the compartment A, which yielded a constant temperature of $-35°$ F. There was also provided a larger outer compartment B, filled with the freezing mixture No. 2, of snow and ordinary salt, giving a steady temperature of 0° F., the latter mixture, No 2, completely enclosing the inner and coolest freezing preparation, No. 1. Good results were obtained by using this arrangement. Previous to mixing, large quantities of the snow and calcium chloride crystals were stored and maintained separately at a temperature of 0° F. in other vessels, and the respective freezing mixtures, No. 1 in compartment A, and No. 2 in compartment B, surrounding the ice tank were constantly renewed during the experiments from these cold stores. Thermometers were inserted in the mixtures and also in the ice during the experiments. The preceding description refers to the maintenance of the ice block at the lower temperature of $-35°$ F. for the observations required at that temperature.

For the observations at 0° F. the ice block was surrounded only by the freezing mixture of snow and salt placed for these experiments in compartment A, and the ice block was encircled by snow only for

the experiments at 32° F. On repeating the experiments in every instance, the water for the ice block was first frozen by the application of a temperature of 0° F., which was afterwards reduced to −35° F. In making the observations, the extent of the penetration of the steel rod at the latter low temperature was first taken; the ice was then allowed gradually to acquire throughout a temperature of 0° F., and its penetrability ascertained; the ice block was afterwards allowed to reach the temperature of 28° and 32° F., and the final measurements obtained. The results recorded are the average of numerous measurements taken directly at different places on the ice block a sufficient distance apart, the indentation caused by the previous penetration of the rod being filled with water, which rapidly froze up. The variation in penetrability at different places on the ice block when measurements were taken at the same temperature was not great.

The polished steel rod used for ascertaining the penetrability was 16 inches long and 0·292 inch diameter; its extremity was a flat disk, so as to avoid any liability of shearing action. The rod was maintained in an upright position by a suitable arrangement of guides, and error arising from its conductivity was obviated by surrounding it throughout its length with fine sawdust contained in a loosely fitting bag which surrounded it. The weight, of $181\frac{1}{2}$ lb. (inclusive of the weight of the platform and guides), was placed on a sliding wood platform working in a frame, the whole weight resting during experimentation on the top of the steel rod (see fig. 1).

Repeated observations were made in the above manner with the results recorded on Diagram I.

I also made a large number of experiments on the plasticity of natural lake or pond ice, which were conducted in a somewhat similar manner; the results showed a greater absence of uniformity in the amount of penetration when compared with results at a similar temperature obtained from the specially prepared pure ice blocks. The observations were taken on the surface of the ice of a large artificial lake or dam, being a storage reservoir for Wortley Iron Works, about 4 acres in extent, the depth varying from about 8 to 10 feet, the thickness of the ice being given on Diagram II. The water of this pond is still, no current of water passing through it; it is therefore practically a small lake. The observations were taken after sunset, and mostly throughout the long cold nights, so as to avoid, as far as possible, any influence of the sun on the surface of the pond ice. A number of measurements were taken adjacently in one locality of the pond, the apparatus being removed to another part for another set of observations, and so on, till the completion of the results. The observations were taken at various periods extending over some time. Thermometers were inserted in the ice, and the atmospheric tem-

perature was also regularly taken; the latter corresponded with the temperature of the ice. The results are given on Diagram II. In connexion with the influence of the composition of water on the plasticity of the ice frozen therefrom, it may be desirable to give an analysis of the water supplying the pond, which was as under:—

Table I.—Analyses of Water.

Results in Grains per Gallon.

	Total residue.	Inorganic matter.	Loss on ignition.	Total sulphates as (SO_3).
Dry seasons...	15·68	11·70	3·58	3·29
Rainy seasons.	11·31	7·56	3·75	2·93

Analysis of sample of water, during a very dry season.
Results in grains per gallon.

Deposit on boiling	0·30	
Iron (Fe)	0·28	
Calcium (Ca)	3·29	
Magnesium (Mg)	1·44	
Chlorine (Cl)	0·69	
(SO_4)	2·88	$= SO_3$ 2·4
	8·88	
Total inorganic matters ...	8·40	

The above analyses of the water during dry seasons are the average of nine different analyses at periods extending over six years, and the analyses of the water during rainy seasons are the average of ten analyses at various periods during six years.

The reaction of the water with litmus was slightly acid, and sulphates were generally present in quantity.

A number of experiments were made to ascertain whether any portion of the saline constituents of the pond water was taken up into the ice during crystallisation. Contrary to expectation, and instead of the ice being found perfectly pure and free from saline matters, it was noticed that the composition of the natural ice was materially affected by the presence of a proportion of the salts of the water from which the ice was crystallised. Roughly speaking, the proportion of inorganic matter found in the melted ice would be about 10 per cent. of the total inorganic salts contained in the pond water from which it was frozen; it was also observed that there was a great propor-

tionate preponderance of organic matter in the ice compared with the water. The experiments were made as follows:—Portions of the ice were taken from numerous places on the pond, and very thoroughly washed with distilled water, the ice was then melted in large glass beakers, and the melted ice was found to be perfectly clear and translucent, there being no deposit after the water had stood for a considerable time. The melted ice, in quantities of half a gallon, was evaporated to dryness in a platinum basin, the residue dried at 212° and weighed, being subsequently ignited and again re-weighed. The results are given on Table II. The results obtained confirm the observations made by Buchanan on the composition of ice in Arctic seas; see remarks hereon towards the close of this Memoir.

Table II.—Analyses of Pond Ice.

Results in Grains per Gallon of the Melted Ice.

Experiment No.	Total residue.	Inorganic matter.	Loss on ignition.	Examination of the inorganic matters. Result in grains per gallon of melted ice.
1	1·70	0·92	0·78	
2	1·84	1·10	0·74	Iron (Fe)...... 0·110
3	1·86	0·90	0·96	Calcium (Ca)... 0·207
4	1·80	0·94	0·86	Magnesium (Mg) 0·0615
5	1·42	0·84	0·58	SO_4.......... 0·461 = SO_3 0·385
6	1·47	0·91	0·56	
Average..	1·68	0·93	0·75	Chlorides were also present.

The penetration of the steel rod into pure ice at constant temperature of −35° F. is shown on Diagram I by curve I; at 0° F. by curve II; at 28° F. by curve III; and at 32° F. by curve IV.

In the experiment, curve II, the needle was allowed to remain on the ice for a total period of 42 hours, the penetration at 18 hours from commencement was 0·906 inch, at 30 hours 1·031 inch, and at 42 hours fiom commencement 1·187 inch.

The penetration of the steel rod into pond ice at 28° F. is shown on Diagram II by curve I, and at 32° F. by curve II.

The pond ice, curve I, was $6\frac{1}{4}$ inches thick, and curve II, $5\frac{1}{8}$ inches thick.

DIAGRAM I.—Plasticity of Pure Ice, as shown by penetration of steel rod therein, at temperatures stated.

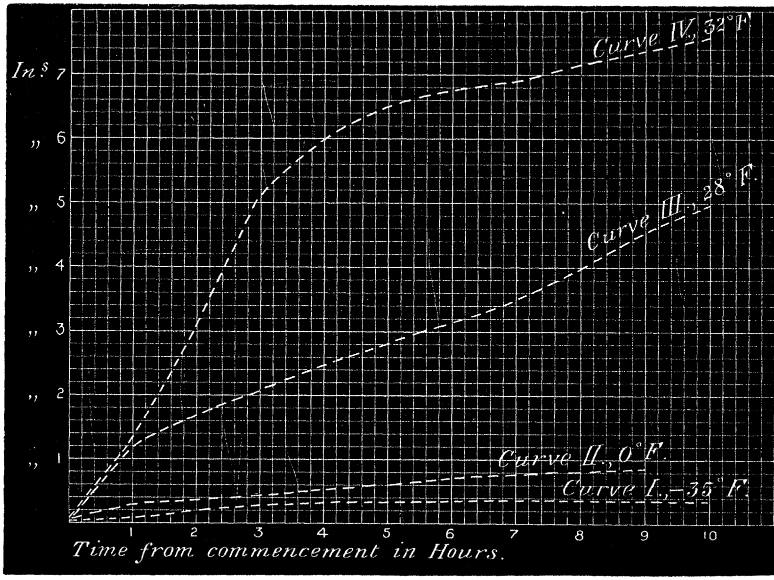


DIAGRAM II.—Plasticity of Pond Ice, as shown by penetration of steel rod therein, at temperatures stated.

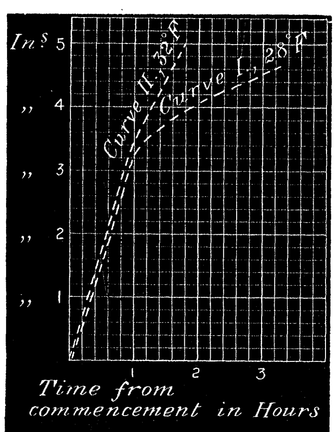


Table III.

Penetrability of steel rod into pure ice. Temperature of ice rising gradually from 0° to 32° F.		
Time from commencement.	Temperature of ice in degrees Fahrenheit.	Penetration of steel rod.
		inches.
3 hours.	10·00	0·458
4 "	12·33	0·604
5 "	14·00	0·781
6 "	17·33	0·948
7 "	19·00	1·125
8 "	20·00	1·271
9 "	20·67	1·427
10 "	21·33	1·604
11 "	22·00	1·750
12 "	22·67	1·937
13 "	23·33	2·104
14 "	24·33	2·250
15 "	24·67	2·448
16 "	25·33	2·635
17 "	25·67	2·777
18 "	26·33	2·888
20 "	26·67	3·124
21 "	27·33	3·339
22 "	27·67	3·502
23 "	28·00	4·021
26 "	28·33	4·423
27 "	29·00	4·806
29 "	29·67	5·174
31 "	30·00	5·583
34 "	31·33	6·375
35 "	31·67	6·661
38 "	31·67	7·155
39 "	31·67	7·483
51 "	32·00	8·625
89 "	32·00	10·125

The above results are the average of three sets of observations made on a cylinder of pure ice 2 feet $1\frac{1}{2}$ inches long, 2 feet $1\frac{1}{2}$ inches diameter, weighing 470 lbs.

Table IV.

Time from commencement.	Penetration of steel rod into pure ice, the ice gradually rising in temperature from 26° to 32° F., and then remaining at 32° F., and subsequently gradually softening.					
	Experiment No. 1.		Experiment No. 2.		Experiment No. 3.	
	Tempera- of ice in degrees Fahr.	Penetration of steel rod No. 1 in inches.	Tempera- of ice in degrees Fahr.	Penetration of steel rod No. 2 in inches.	Tempera- of ice in degrees Fahr.	Penetration of steel rod No. 3 in inches.
hrs. m.						
0	26	0·000				
5	26	2·750				
15	26	3·000				
30	26	3·250				
45	27	3·500				
1 0	28	3·750				
2 0	28	4·125				
3 0	28	4·375				
4 0	28	4·625				
8 0	28	5·375				
13 30	28	6·562				
19 0	28	7·750				
46 20			32	0·000		
46 25			32	5·000		
46 40			32	5·250		
46 55			32	5·562		
47 10			32	5·875		
47 25			32	6·062		
47 40			32	6·187		
48 40			32	6·562		
48 45					32	0·000
48 50					32	5·375
48 55					32	6·562
49 5					32	7·000
49 10					32	8·500
49 15					32	9·500

The above observations were made on a cylinder of pure ice 2 feet $1\frac{1}{2}$ inches long, 2 feet $1\frac{1}{2}$ inches diameter, and weighing 470 lbs.

In experiment No. 2, the ice cylinder had remained at a temperature of from 26° to 28° F. for 46 hours 20 minutes previous to commencing the experiment with steel rod No. 2.

In experiment No. 3, the ice cylinder had remained at a temperatuure of 32° F. for $2\frac{1}{2}$ hours previous to commencing the experiment with steel rod No. 3.

These experiments show that the plasticity of the ice was very

rapidly and considerably increased after reaching, and whilst it afterwards remained at, a temperature of 32° F.

General Remarks.

1st. Referring to the results of Diagram I, and taking the relative penetration of the steel rod at the respective temperatures as an indication of the plasticity of the ice, it will be noticed that there was a considerable reduction of plasticity as the temperature lowered. Regarding as a guide the total depth penetrated by the steel rod, during equal and comparative periods of time (as, for instance, the results at 2, 3, 4, 5, 6, 7, &c., hours, Diagram I, curves 1, 2, 3), into ice at different temperatures, these comparative experiments show, in a majority of instances, that, if the plasticity of the ice at $-35°$ F. be called one, at 0° F. it would be about twice as much, and at 28° F. the plasticity would be about four times as great as at 0° F., or eight times as much as at $-35°$ F. When the ice was maintained at a temperature of 32° F., it will be seen that the plasticity very considerably increased, this being probably owing to the reduced cohesion at this temperature between the faces of the ice crystals forming the mass.

2nd. It will be further noticed that the plasticity was greater during the gradual molecular changes occurring in course of the slow rising of temperature from 0° F. to 32° F., see results on Table III, than when the ice was maintained at even temperatures, as in the experiments on Diagram I.

3rd. Reverting to the observations on Table IV, if the time required for the steel rod to penetrate a certain depth, say, $6\frac{1}{2}$ inches, into the ice under conditions of experiments 1, 2, and 3, Table IV, be taken as an indication of the relative plasticity of the ice under conditions of these experiments, it will be seen that the plasticity was roughly about 579 per cent. greater in No. 2 than No. 1, and 1400 per cent. greater in No. 3 than in No. 2, these results showing proportionately the rapid manner in which the mass of ice was becoming internally plastic, although retaining an outward apparent rigidity. The Rev. Coutts Trotter, in his paper ('Roy. Soc. Proc.,' vol. 38, 1885, p. 92), states that "the 'viscosity' of ice probably diminishes very rapidly with the temperature," and it appears probable from the experiments of M. Person ('Comptes Rendus,' vol. 30, 1850, pp. 526—528) that $-2°$ C. is the temperature at which ice begins to soften. The Rev. C. Trotter, after summarising the experimental evidence, also arrives at the conclusion that the general interior and bottom portions of a glacier, near the surface of the earth, are of a constant temperature of about 0° C., and my experiments recorded on Diagrams I and II and Tables III and IV demonstrate the greater

plasticity of ice, in the mass, at similar temperatures. Mr. Trotter further remarks that "the supposition that, while ice at 0° C. is sensibly viscous, the viscosity diminishes rapidly with the temperature is in complete accordance with the facts of the changes which take place in a glacier during the winter." The comparatively great contractibility in ice observed at considerably reduced temperatures, see my paper on "Observations on Pure Ice and Snow" ('Roy. Soc. Proc.,' vol. 40, 1886, p. 544), accounts for the great reduction in its plastic properties. This is in full accord with the practical cessation of motion in glaciers during the cold of winter. I believe that the plastic properties of ice in the mass are variable, and are also, to some extent, influenced by the rapidity or otherwise of its crystallisation. Thus, a mass of water rapidly frozen at an intensely low temperature would, no doubt, crystallise into a larger number of smaller crystals than those which would result from a more slow solidification of the mass of water at a comparatively higher temperature of freezing.

4th. It will be noticed, on comparing the results of Diagrams I and II, that the plasticity of the naturally frozen pond ice was manifestly greater than that of the artificially prepared pure ice, and the difference in results may, to a certain extent, probably be accounted for by difference of composition of the respective frozen waters and ice (the block ice being frozen from pure distilled water, the composition of the pond water and ice frozen therefrom being given on Tables I and II); I think, also, the difference was, to some extent, owing to the direction from which the pond ice was frozen, viz., from the surface only. Further, this comparative difference in the behaviour of the pond ice was doubtless owing to a portion of the saline constituents of the water interspersing, during congelation, between the faces of the individual crystals of ice, thereby tending to reduce the cohesion of the mass as a whole and increasing its plasticity. Mr. J. Y. Buchanan, F.R.S., has shown that in Arctic ice, contrary to expectation, the whole of the salts do not separate from sea-water ice during congelation, but that they remain interspersed amongst the interstices of the crystalline mass ("Ice and Brine," 'Edinburgh Roy. Soc. Proc.,' vol. 14, 1888, p. 129). My experiments on Table II also show that the composition of pond or natural river ice is affected in a similar manner, and afford confirmation of the views held by Buchanan on the composition of sea-water ice in Arctic regions. The fact of the pond ice having been slowly crystallised would further tend to modify its physical properties, compared with ice rapidly crystallised by an intensely low temperature, simultaneously acting only from the bottom and sides of the mould or tank. Measurements of the expansibility of ice may also be affected accordingly as such measurements are taken either longitudinally or

transversely to the line of the cold crystallising force, and from my former experiments in this direction ('Roy. Soc. Proc.,' vol. 40, 1886, p. 544), I think there appear substantial indications that ice may expand unequally in different directions. Messrs. McConnel and Kidd have shown, in their experiments with glacier ice, that "ordinary ice, consisting of an irregular aggregation of crystals, exhibits plasticity, both under pressure and under tension at temperatures far below the freezing point, down to $-9°$ at least, and probably much lower." The experiments recorded on Diagram I now practically demonstrate the latter supposition, and I found the plasticity at the lower temperature to be very considerably reduced. Mr. J. Y. Buchanan, F.R.S., in his paper on "Ice and Brine" ('Edinburgh Roy. Soc. Proc.,' vol. 14, 1888, p. 129), has expressed notions of the plasticity and flow of glacier ice which tend to confirm the views of Messrs. McConnel and Kidd on this subject. In this direction the experiments on pure ice, Diagram I, compared with those on pond ice, Diagram II, have shown that ice frozen from water containing saline constituents is more plastic than the ice frozen from pure distilled water.

I hope that the experiments of this memoir may help to afford information in connexion with the interesting subject of the plasticity of ice.

Appendix.

Attention has very recently been drawn to the manner in which lake ice has a tendency to crystallise, in a series of interesting letters published in 'Nature,' 1889, by Mr. Thomas H. Holland, Mr. T. W. Backhouse, Mr. T. D. Latouche, Messrs McConnel and Kidd, and others. I have myself also frequently noticed the six-rayed starlike figures and skeleton triangular forms on natural pond ice, and other similar indications of the tendency of lake ice to the hexagonal form of crystallisation.

III. "The Passive State of Iron and Steel."—Part I. By THOS. ANDREWS, F.R.SS.L. and E., M.Inst.C.E. Received May 18, 1890.

The singular metallurgical phenomenon of the passive state of iron presents many features of interest, affording a wide field for original research. The knowledge we possess on this peculiar and obscure subject is not, however, very extensive, owing possibly to the difficulties encountered in devising suitable methods of research in relation thereto. The author, therefore, approached the investigation with considerable diffidence, feeling greatly the difficulties accompanying

FIG. 1.

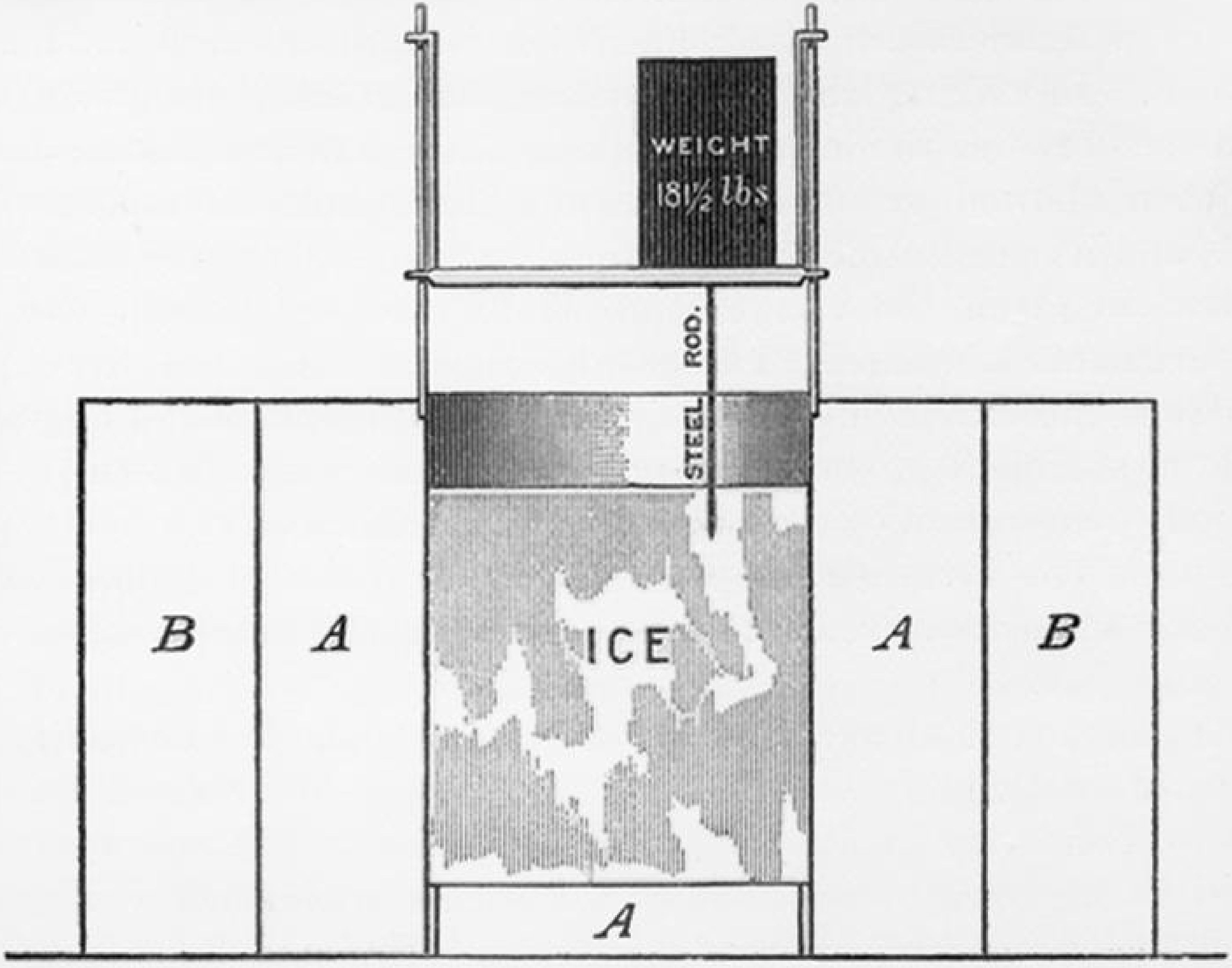


Diagram I.—Plasticity of Pure Ice, as shown by penetration of steel rod therein, at temperatures stated.

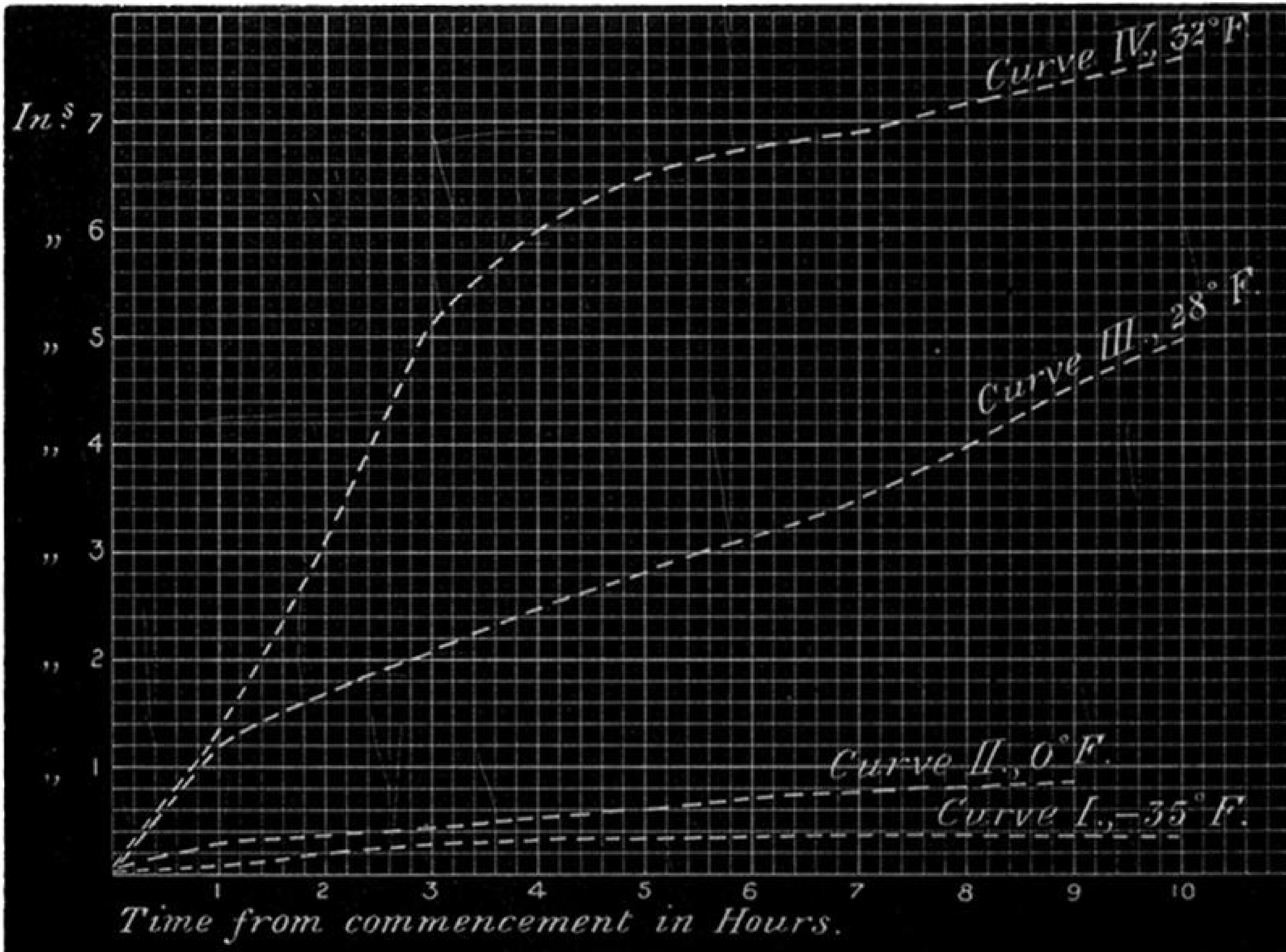


DIAGRAM II.—Plasticity of Pond Ice, as shown by penetration of steel rod therein, at temperatures stated.